

Spatially Broadband Parametric Amplification: Quantum-Noise Correlations and Noiseless Amplification of Images

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Abstract:

The success of many precision measurements often depends on the use of amplifiers. The sensitivity of these measurements is, therefore, limited by the amount of noise that the amplifier adds to the signal. For electronic and microwave signals, the noise floor is determined by thermal fluctuations. At optical frequencies, however, the thermal noise becomes negligibly small. In that case, the noise floor of a phase-insensitive amplifier, i.e., a linear optical amplifier whose gain does not depend on the signal phase, is determined by a fundamental quantum limit, which arises ultimately from zero-point field fluctuations. In a typical optical amplifier, these fluctuations cause spontaneous emission of photons, resulting in added noise to the signal. For a coherent-state input, the degradation of signal-to-noise ratio (SNR) at the output approaches 3 dB for high gain. The noise owing to the zero-point fluctuations, however, can be avoided by employing a proper phase-sensitive amplifier (PSA) that either amplifies or de-amplifies the input signal depending on its phase [Caves, Phys. Rev. D, Vol. 26, 1817 (1982)]. This noise-free property of a PSA is related to the fact that every act of spontaneous or stimulated emission in such a device produces a pair of correlated photons, whose quantum correlation can be utilized for noise cancellation.

The quantum correlations imposed by a PSA have been exploited to produce non-classical states of light. A practical realization of a PSA is a traveling-wave optical parametric amplifier (OPA), which provides broadband gain not only in the temporal domain, but also in the spatial domain. The spatially broadband nature of the OPA suggests its potential use for noiseless amplification of spatial-domain signals, i.e., images, as well as for sub-shot-noise microscopy [Kolobov and Kumar, Opt. Lett., Vol. 18, 849 (1993)]. The spatially broadband gain of the OPA has been exploited previously in classical imaging experiments, such as parametric up-conversion of infrared images to the visible, edge enhancement, and time-gated image recovery. In contrast, our work addresses the quantum-noise issues in image

amplification. We have measured quantum correlations between the corresponding spatial frequencies of a parametrically amplified (signal) image and its generated conjugate (idler) image, and found the direct-detected difference noise to be ~5 dB below the shot-noise level [Marable, Choi, and Kumar, Opt. Ex., Vol. 2, 84 (1998); <http://epubs.osa.org/oearchive/source/4000.htm>]. We have also operated such a spatially broadband parametric amplifier in its phase-sensitive configuration and demonstrated that noiseless amplification of images is possible. Furthermore, image pre-amplification before loss was shown to improve the detected SNR [Choi, Vasilyev, and Kumar, Phys. Rev. Lett., Vol. 83, 1938 (1999)].

Such noiseless amplification of optical images has great potential in situations where the incoming signal is necessarily weak, but has a phase that can be related to the PSA phase. Two important scenarios are: i) Imaging through turbid media, such as in medical imaging through highly scattering tissue. ii) Imaging through foliage, such as identifying hard targets (military equipment) hidden behind trees and other vegetation. In both cases, an incident wave is heavily scattered. As a result the return signal is necessarily weak, but has a phase relation with the incident wave. However, the return signal needs to be time gated (for discrimination from the scattered radiation) and amplified with as low degradation in SNR as possible. A spatially broadband pulse-pumped OPA operated as a PSA, as that used in our experiments, is especially suited for both these applications.